All-solid-state doubly resonant sum-frequency continuous-wave laser at 555 nm

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A new kind of resonator for doubly resonant continuous-wave (CW) intracavity sum-frequency mixing (SFM) is presented. A coherent radiation of 327 mW at 555 nm is generated by mixing 1342-nm Nd:YVO_4 laser and 946-nm Nd:YAG laser. The M^2 beam quality factor of the sum-frequency mixed yellow-green laser is less than 1.7. The low-noise characteristic of the yellow laser is demonitrated.

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Coherent continuous wave (CW) light sources in the visible spectral range have become interesting for many technical applications in medicine, lithography, communications, display, and other areas. Recently, frequency-doubled, diode-pumped Nd^{3+} lasers have been established as compact, efficient, all-solid-state sources in the blue, green, and red spectral regions[1−6]. Unfortunately, radiation in the spectral region between 550 and 650 nm cannot be generated with second-harmonic generation because of the absence of efficient fundamental lasers. However, radiation near 620 and 590 nm is required for display technology and medical applications, respectively. Therefore, other ways of generating coherent light at these wavelengths have to be found. One possibility is sum-frequency generation (SFG), in which coherent frequencies of ω_1 and ω_2 are mixed, generating radiation of frequency $\omega_3 = \omega_1 + \omega_2$.

Sum-frequency mixing (SFM) was firstly demonstrated in the 1960's, but for many years it was used mainly for heterodyne signal detection. In the past few years, diode-pumped singly resonant SFM and doubly resonator SFM of Nd^{3+} lasers have been studied[7−9].

In this letter we propose a doubly resonant intracavity approach to generate sum-frequency laser at 555 nm. The schematic of the system is shown in Fig. 1. The double resonator consisted of one shared and two separated arms. The separated arms involved the laser crystals and independently alignable laser resonators. The separated arms were joined with a diachronic beam splitter. Nd:YVO_4 at 1342 nm and Nd:YAG at 946 nm were chosen as laser materials to generate the yellow spectrum at the 555 nm.

The Nd:YVO_4 ($3\times3\times5$ (mm)) crystal was 0.5% Nd^{3+} doping, and the Nd:YAG ($\Phi \times 3$ (mm)) was 1% Nd^{3+} doping. One side of Nd:YVO_4 was coated anti-reflection (AR) at 808 nm and high-reflection (HR) at 1342 nm and other side was AR at 1342 nm. One side of Nd:YAG was coated AR at 808 nm and HR at 946 nm and other side was AR at 946 nm. In addition, considering that the stimulated emission cross section at 946 nm (0.43×10^{-19} cm^2) was estimated to be $\sim$ 10% of that at 1064 nm (4.6×10^{-19} cm^2) and quantum efficiency of 946 nm was also lower than that at 1064 nm[10], the highly reflecting coating of the Nd:YAG crystal was also of low reflectance near 1064 nm to avoid laser oscillation at this wavelength; and considering that the stimulated emission cross section at 1342 nm (7.6×10^{-19} cm^2) was estimated to be $\sim$ 30% of that at 1064 nm (25×10^{-19} cm^2) and quantum efficiency at 1342 nm was also lower than that at 1064 nm, the highly reflecting coating of the Nd:YVO_4 crystal was also of low reflectance near 1064 nm to avoid laser oscillation at this wavelength[11]. One side of beam splitter was coated AR at 1342 and 1064 nm and other side was HR at 946 nm and AR at 1064 nm. Concave of output mirror ($\rho = 200$ mm) was coated HR at 1342 and 946 nm and AR at 555 nm and other side was AR at 555 nm. The laser crystals were wrapped with indium foil and mounted in a semiconductor cooled copper blocks.

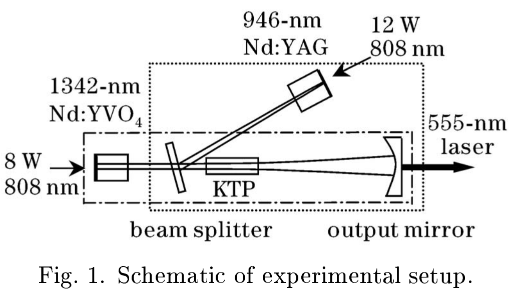

Fig. 1. Schematic of experimental setup.

KTP has to be critically phase-matched for type II SFG. Calculated by SNLO[12], $2\times2\times7$ (mm) flux grown KTP crystal cut at $\theta = 63.7°$, $\phi = 0°$ was located in the shared arm. This device permits type I critical phase-matching for 1342 nm (o-light) and 946 nm (e-light), producing 555 nm (o-light). An effective nonlinear coefficient of $d_{\rm eff} = 3.12$ pm/V, and relatively 2.38° of walk-off angle of the 1342-nm beam from the phase-matching direction are expected. Two ends of KTP was coated AR at 1342, 946, and 555 nm. Two pump sources used in the experiments were commercially available fiber-coupled diode laser arrays, which delivered the maximum output powers of 8 and 12 W respectively at the wavelength of 808 nm from the fiber bundle ends. The fibers were drawn into round bundles of 0.4-mm diameter with the numerical aperture of 0.22.

The two pump beams from the fiber bundle ends were focused into the laser crystals with the same spot diameter of 0.4 mm. The pump light was focused inside each crystal with two achromatic collimating lenses. The cavity length was 58 cm for 1342-nm oscillation and the

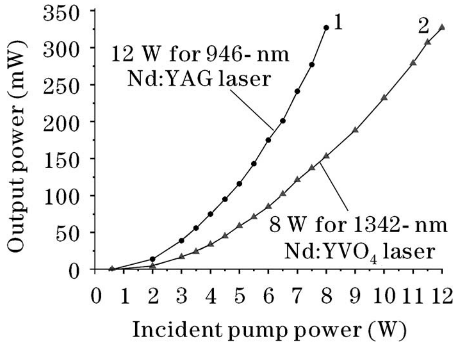

Fig. 2. SFM 555-nm output power versus pump power into Nd:YVO_4 (1) or Nd:YAG (2).

other cavity length was 46 cm for 946-nm emission. The temperature of laser diode arrays, Nd:YVO_4, Nd:YAG, and KTP were strictly controlled respectively.

The output power as a function of incident pump power is shown in Fig. 2. The curve 1 is the output power of 555-nm laser versus pump power injected into Nd:YVO_4 when pump power for Nd:YAG is 12 W, curve 2 is the output power of 555-nm laser versus pump power into Nd:YAG when pump power for Nd:YVO_4 is 8 W. The threshold was measured to be 0.6 W, the maximum output power was 327 mW. It is obvious that the slope efficiency increases sharply near the full pump power, and the reason is exactly that the laser configuration is designed at the point of full pump power.

The noise property was tested for output power of 327 mW. From Fig. 3, the low-noise characteristic of the 555-nm laser is demonstrated.

The TEM_{00} energy distribution diagrams of 555-nm laser recorded by a beam profiler (made by Photon Inc.) are showed in Fig. 4.

In conclusion, we have demonstrated doubly resonant SFM of two laser diode array pumped continuous wave Nd^{3+} lasers to generate coherent radiation in the yellow

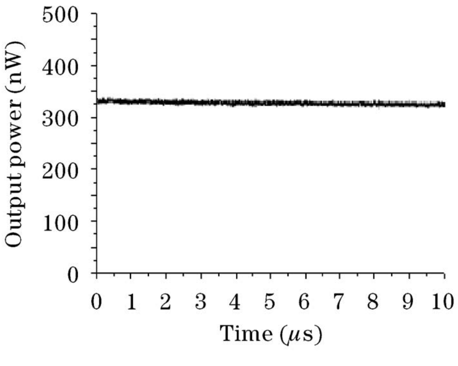

Fig. 3. Output power of 555-nm laser with low-noise operation.

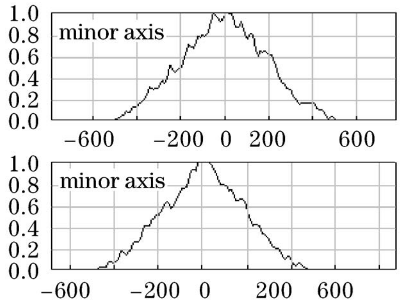

Fig. 4. TEM_{00} energy distribution of far-field spots.

spectral region at 555 nm. A laser with output power of 327 mW, low noise and good beam quality was obtained. The M^2 beam quality factor of the sum-frequency laser was measured by the knife-edge technique to be less than 1.7. The above structure was experimentally illustrated to be an efficient way to obtain 555-nm laser.

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